This is a draft document intended to be chapter 4 of the EPA R10's problem assessment for the temperature TMDL for the Columbia and Snake rivers. Chapter 4 is intended to give the reader of the problem assessment an appreciation for the effects of increased water temperature on native fish species inhabiting the TMDL study area in Columbia River basin. The other parts of the assessment can be found at: www.epa.gov/r10earth/columbiamainstemtmdl.htm

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4.0 Effects of Increased Water Temperature on Native Salmonids and Sturgeon

4.1 General

Chapter 3 of this problem assessment described the changes to the temperature regime of the Columbia and Snake rivers associated with the development of water resources. The purpose of this chapter is to evaluate the effect of water temperature on chinook salmon (*Oncorhynchus tshawytscha),* sockeye salmon (*O. nerka*), coho salmon (*O. kisutch),* steelhead trout (*O. mykiss*)*,* bull trout (*Salvelinus confluentus*), and white sturgeon (*Acipenser transmontanus*). Water temperature affects all life stages of these fish. It directly affects spawning, rearing, feeding, metabolic processes including growth, and overall survivability. Further, the incidence and intensity of some diseases are directly related to increased water temperatures. Indirect effects of increased water temperature include changing food availability, increasing competition for feeding and rearing habitat, and enhancing the habitat for predatory fishes.

The effects of increased temperature on spawning, growth, migrations (including smoltification), disease, predation, distribution, and other sub-lethal and lethal effects are addressed below in sections 4.2.1 to 4.2.7 for the three salmon species mentioned above and for the steelhead trout. The effects of increased temperature on bull trout and white sturgeon are assessed separately in sections 4.2.8 and 4.3.1, respectively. Since only adult bull trout are believed to periodically overwinter in the study area, the assessment will only consider the effects of increased temperature on growth, movement, and distribution for this life stage. Spawning and rearing for this species occur in cold-water tributary streams throughout the Columbia River basin (Ratliff & Howell 1992, Rieman et al. 1997). For the white sturgeon, only water temperatures needed for successful reproduction will be addressed. From our review of the literature, it appears that the time period for embryonic and early development is the most critical temperature-dependant life stage for the white sturgeon (Cech et al. 1984, Wang et al. 1987).

In the comprehensive literature review conducted for this assessment, an attempt was made to find and review all of the most important information available on the temperature-related factors affecting the salmonids mentioned above and the white sturgeon.

4.2 Salmonids

Native salmonid populations in the Columbia River basin have undergone serious declines resulting in the extinction of numerous runs. At present, 12 salmon and steelhead trout stocks in the basin are listed as threatened or endangered under the Endangered Species Act. Listed stocks located above Bonneville Dam are spring chinook and steelhead from the Upper Columbia River, steelhead from the Mid Columbia River, and spring/summer and fall chinook, sockeye and steelhead from the Snake River. Listed stocks below Bonneville Dam are chinook and steelhead from the Lower Columbia, chinook and steelhead from the upper Willamette River, and the Columbia River chum *(O. keta*). Native runs of coho and chum are extinct in the basin above Bonneville Dam, and below Bonneville their populations are depressed (Independent Scientific Group 1996, National Science & Technology Council 2000).

With regard to chinook salmon, spring-summer and fall races inhabit the basin. These races are also referred to as stream-type and ocean-type chinook salmon, respectively. The life cycles differ in that the spring-summer chinook usually rear in freshwater for one or more years, while fall chinook usually migrate to the ocean in their first year of life. Depending on growth rates, there may be exceptions to these migratory patterns. Slow growing fall chinook may outmigrate in their second year and fast growing spring-summer chinook may leave in their first year of life (Healey 1991). On first inspection, it would appear that spring-summer chinook would have the greatest potential exposure to increased water temperatures due to their longer freshwater residency, but they more commonly rear high in the tributaries that have cooler water and usually migrate to the ocean in the spring. In comparison, fall chinook spawn lower in the basin and migrate to the ocean in the late summer or early fall when water temperatures are at the highest point for the year (unpublished 2001 data from the Fish Passage Center).

To the extent that information is available, the effects of water temperature on the juvenile and adult life stages of chinook salmon, sockeye salmon, coho salmon, steelhead trout, and bull trout are summarized in Tables 4-1, 4-2, 4-3, 4-4, and 4-5, respectively. Life stages included in the juvenile classification are alevin, parr, fry, fingerlings, subyearling, yearling, and smolts. Adult studies include "jack" salmon, which are predominantly males that return early from the ocean and mature precociously. The effects of, or levels of concern for, water temperature listed in these tables are only for those life stages that occur within the study area. For example, fall chinook spawn in main channel areas in the basin, but other salmonids do not. Therefore, water temperatures that may cause increased mortality during egg incubation are provided only for fall chinook salmon.

4.2.1 Effects of increased temperature on spawning

Fall chinook salmon appear to be the only salmonid species that spawns in the main channels of the Columbia and Snake rivers. Except for limited main-stem spawning below Wanapum, Rock Island, and Wells dams in the Columbia River and below three of the lower Snake River dams (Dauble & Watson 1997), the main fall chinook spawning areas are located in the free-flowing Snake River below Hells Canyon Dam (Groves & Chandler 1999) and in the Hanford Reach (Dauble et al. 1989).

Fall chinook spawn from approximately mid-October to the third week of November in the Hanford Reach and from mid-October until mid-December in the Snake River. Water temperatures associated with spawning are similar for the two areas. Spawning occurs at daily mean temperatures ranging from 12 - 18.5 °C in the Hanford Reach (Dauble & Watson 1997) and at mean weekly temperatures ranging from 5 - 16 °C in the free-flowing Snake River (Groves & Chandler 1999). The higher temperature in each range occurs at the start of each spawning season after which the water temperature decreases during the winter incubation period.

Bell (1986) provides recommended spawning and incubation temperatures for nearly all salmonid fishes inhabiting the Columbia River basin. For fall chinook salmon, Bell (1986) recommends 5.6 - 13.9 °C and 5 - 14.4 °C, respectively, for spawning and incubation. The higher and lower values are threshold temperatures beyond which mortality increases.

A review completed by Hicks (2001) suggests that constant temperatures above 9 - 10 °C and below 5 °C may reduce the survival of chinook salmon embryos and alevins. For optimum protection from fertilization through early fry development, Hicks (2001) recommends that the weekly average of the daily maximum temperature at the time of fertilization not exceed 11 - 12 °C and that individual daily maximum temperatures not exceed 13.5 - 14.5 °C. These concerns and recommendations are repeated by McCullough et al. (2001) in a review of the same information.

Table 4-1. The effects of water temperature on chinook salmon.

Temp °C	Effect/Concern	Life Stage[1]	Reference
14-15	Increased egg mortality during incubation (fall chinook) Highest survival in hatcheries (<14 °C) Upper limit for optimum range Smolting impaired, migration stopped	Eggs A J J	Bell 1986, Hicks 2001 Leitritz & Lewis 1976 Brett 1952, Brett et al. 1982, Bell 1986 McCullough et al. 2001 Myrick & Cech 2001
16-17	Initial losses from diseases Handling stresses broodstock (>15 °C) Increased infertility, abnormal egg and embryological development	J-A A A	Fryer & Pilcher 1974, Fryer et al. 1976 Marine 1992 Marine 1992, Berman 1990 Hinze et al. 1956
18-19	Shallow water feeding areas abandoned Lethal chronic exposures	J A	Curet 1993, Connor et al. 1999 Marine 1992
20-21	Thermal barrier to migration Lethal chronic exposures Reduced or no growth Increased predation	A J J J	Hallock et al. 1970, Stabler et al. 1981 Beacham & Withler 1991 Brett et al. 1982, Harmon et al. 2001 Vigg et al. 1991, Vigg & Burley 1991
22-23	Lethal (22 °C), acclimated at 19 °C High disease mortality High mortality of hatchery releases	A J J	Coutant 1970 Holt et al. 1975 Baker et al. 1995
24-25	Lethal threshold (23.5-24.7 °C) Lethal (25 °C), acclimated at 20 °C	J J	Blahm & McConnell 1970 Brett 1952
26-28	High mortality in 24 hr after 67 minute exposure to 27 °C and return to 15 °C Increased predation after 67 second exposure to 28 °C and return to 15 °C	J J	Dean & Coutant 1968 Coutant 1973

Note: 1. J = juvenile, A = adult.

Table 4-2. The effects of water temperature on sockeye salmon.

Temp °C	Effect/Concern	Life Stage[1]	Reference
12-13	Migration reduced or stopped	J	Foerster 1937, Brett et al. 1958
14-15	Optimum for growth, swimming speed Maximum swimming speed Physiologically ideal in freshwater Optimum for river migration	J A J A	Brett et al. 1958, Bell 1986 Brett & Glass 1973 Brett 1967 Bell 1986
16-17	Initial losses from diseases Reduced reproductive capacity Outmigration ended, average temperature was 17.5 °C over 8 yrs	J-A A J	Ordal & Rucker 1944 Servizi & Jensen 1977 Bouck et al. 1975 Foerster 1937
20-21	Lose upstream orientation Migration blocked No or poor growth Increased predation	A A J J	Farrell 1997 Major & Mighell 1966 Donaldson & Foster 1941 Vigg et al. 1991, Vigg & Burley 1991
22-23	Lethal threshold (22.5-23.5 °C) Death in 2-5 days High mortality in 1 day, acclimated at 11 °C	J A J-KO[2]	McConnell & Blahm 1970 Servizi & Jensen 1977, Bouck et al. 1975 Black 1953
24-25	50% mortality with 6.7 hrs exposure, acclimated at 15 °C	J	Brett 1952

Notes: 1. J = juvenile, A = adult, 2. KO = Kokanee, a lacustrine stock of sockeye salmon.

Table 4-3. The effects of water temperature on coho salmon.

Temp °C	Effect/Concern	Life Stage[1]	Reference
12-13	Prevents premature smoltification (<12°C)	J	Wedemeyer et al. 1980
14-15	Optimum hypoosmoregulatory capacity Optimum growth (15 °C)	J J	Clarke & Shelbourn 1980 Jobling 1981
16-17	Initial losses from diseases Greatest growth (17 °C) Fish always present (MWMT[2] <16.3 °C)	J J J	Fryer & Pilcher 1974, Fryer et al. 1976 Clarke & Shelbourn 1980 Welsh et al. 2001
18-19	Fish may be absent (MWMT <18.1 °C)	J	Welsh et al. 2001
20-21	Sublethal stress (diel exposure 6.5-20 °C) Serious loss from disease Very restricted peak in gill ATPase Optimum cruising speed Fish absent or rare in stream (21 °C) Increased predation	J J J J J J	Thomas et al. 1986 Fryer & Pilcher 1974, Fryer et al. 1976 Zaugg & McLain 1976 Brett et al. 1958 Frissell 1992 Vigg et al. 1991, Vigg & Burley 1991
22-23	Fish used cold-water refugia Lethal threshold (23.5 °C)	J J	Bisson et al. 1988 Blahm & McConnell 1970
24-25	Upper lethal temperature 25 °C Lethal exposure 46 min at 26 °C	J A	Brett 1952, DeHart 1974 Coutant 1969

Notes: 1. J = juvenile, A = adult, 2. Maximum weekly maximum temperature.

Table 4-4. The effects of water temperature on steelhead trout.

Temp °C	Effect/Concern	Life Stage[1]	Reference
12-13	Exceeds upper limit of optimum range Smolting inhibited, migration reduced	J J	Bell 1986 Zaugg et al. 1972, Zaugg & Wagner 1973
14-15	Impaired adaptation to seawater Decline in gill ATPase	J J	Myrick & Cech 2001 Adams et al. 1973
16-17	Initial losses from diseases	J	Fryer & Pilcher 1974, Fryer et al. 1976
18-19	Habitat reduced by competition Growth rate declines (>19 °C) Fish used cold-water refugia	J RB[2] J-RB	Reeves et al. 1987 Myrick & Cech 2001 Frissell 1992
20-21	Migration delayed, fish used refugia High disease mortality Increased predation Reduced growth via competition	A J J J	Fish & Hanavan 1948, Stabler 1981 Holt et al. 1975 Vigg et al. 1991, Vigg & Burley 1991 Reese & Harvey 2002
22-23	Upper lethal limit Serious loss from disease	A J	Templeton & Coutant 1970 Fryer & Pilcher 1974
24-25	Upper lethal limit (24 °C) Chronic lethal level (>25 °C)	J J	Bell 1986 Myrick & Cech 2001

Notes: 1. J = juvenile, A = adult, 2. RB = Rainbow trout.

Table 4-5. The effect of water temperature on bull trout.

Temp °C	Effect/Concern	Life Stage[1]	Reference
10-12	Maximum growth	A-J	Buchanan & Gregory 1997 McMahon et al. 1998
	Spawning movements to tributaries	A	Fraley & Shepard 1989 McPhail & Murray 1979
	Highest density in streams (7.8-13.9 °C)	J	Saffel & Scarnecchia 1995
	Higher fitness trends	A	Haas 2001
13-14	Out competed by sympatric salmonids	J A	McMahon et al. 1999 Haas 2001
15-17	Fish not present (>14 °C)	A-J	Goetz 1997
	Decreased fitness (>14 °C)	J	McMahon et al. 1998
	Limits distribution (>15 °C)	A	Shepard et al. 1984
	Thermal block to migration (16 - 18 °C)	A	Thiesfeld et al. 1996 Shepard 1985
18-20	Lowest density in streams (18.3-23.3 °C)	J	Saffel & Scarnecchia 1995
	Reduced feeding efficiency and exhibited signs of stress	J	Selong et al. 2001
	Used thermal refugia	A	Adams & Bjornn 1997
	47% mortality in 60-day exposure (20 °C)	Age-1	McMahon et al. 1999
	21% mortality in 60-day exposure (20 °C)	Age-0	Selong et al. 2001
21-22	54% mortality in 60-day exposure (21 °C)	Age-1	McMahon et al. 1999
	100% mortality in 60-day exposure (22 °C)	Age-0	Selong et al. 2001
	Transition trout to non-trout fish community	J-A BT[2]	Taniguchi et al. 1998

Notes: 1. J = juvenile, A = adult, 2. BT = brook trout.

4.2.2 Effects of increased temperature on growth

Since growth is an integrator of environmental, behavioral, and physiological influences affecting fish, it is a very useful indicator of stress (Jobling 1996). Increased temperature has a profound influence upon growth rates, but the rates are also affected in a field environment by food availability, competition, and other factors. Numerous studies have inferred that if food is abundant in the wild, salmonid growth can be enhanced with increasing water temperature. Conversely, if food is limited, then any substantial temperature increase would result in decreased growth. The growth studies reviewed for this assessment were conducted on captive fish that were fed at levels up to satiation and that lacked the stresses typically found in a field environment. These limitations are important when considering the effects of increased temperature on fish growth using only laboratory studies. Intuitively, we expect lower growth rates to occur in the field given all of the energy requirements that fish need to compete for food and habitat, avoid predators, and to complete migrations to the ocean.

Our review of laboratory and hatchery studies indicates that growth declines or stops for juvenile chinook, sockeye and coho salmon and steelhead trout as water temperature increases into the 18 - 21 °C range. Optimum growth for these species occurs from about 15 - 17 °C (Brett et al. 1969, Banks et al. 1971, Brett 1971, Wurtsburg & Davis 1977, Clark & Shelbourn 1980, Jobling 1981, and Brett et al. 1982).

The above listed fish species are able to survive beyond these optimum ranges; however, growth is eventually reduced. At the higher temperatures most of the food is used for maintenance as metabolic rates are increased (Bjornn & Reiser 1991). Brett et al. (1982) and Thomas et al. (1986) report, respectively, sub-lethal growth stress for chinook at 18.5 - 21 °C and for coho exposed to diel fluctuations of 6.5 - 20 °C. Edsall (unpublished data referenced by the Great Lakes Fishery Laboratory 1970) observed declining growth as water temperature increased to 18 - 20 °C with immature coho salmon that were fed to satiation. Similarly, Donaldson & Foster (1941) noted slight or no growth in sockeye salmon held at 21.1 °C, and loss of weight and mortality at 22.8 °C. Wurtsburg & Davis (1977) studied the effects of temperature, ration level and fish size on juvenile steelhead growth. They measured maximum growth at 16.4 °C and noted that above this temperature growth rates declined rapidly.

Since the steelhead is an anadromous rainbow trout, we also reviewed temperature-limiting growth studies for the rainbow trout. For two strains of resident rainbow trout in northern California, Myrick & Cech (2001) found that growth rates increased with temperature to a maximum near 19 °C and declined rapidly at temperatures above 19 °C. In a series of growth experiments at seven constant and six diel fluctuating temperatures using rainbow stocks from Lake Superior, Hokanson et al. (1977) found that maximum growth occurred at 17.2 °C for the constant temperature treatments which ranged from 8 - 22 °C. For the fluctuating treatments with daily means of 12 - 22 °C and average amplitudes of ± 3.8 °C, maximum growth occurred at a mean temperature of 15.5 °C. Fish exposed to the highest diel fluctuation actually lost weight. All fish were fed to satiation.

4.2.3 Effects of increased temperature on migrations, including smoltification

Two migrations occur during the life cycle of anadromous salmonids. Juveniles migrate to the ocean and after an ocean rearing phase the adults return to their natal streams to spawn. The juveniles undergo parr-smolt transformation (or smoltification) during their journey to the sea. Smoltification is a physiological process that enables a fish to live in salt water, and involves changes in growth, condition factor, body silvering, body moisture and lipid content, and salinity tolerance (Wedemeyer et al. 1980, McCullough et al. 2001). Research conducted on this process has evaluated the concentrations of the gill enzyme ATPase and hypoosmoregulation. Reduced ATPase levels and impaired osmoregulation may result in delayed or ineffective transition to marine waters. With most anadromous salmonids, photoperiod or fish size appear to be the main drivers of smoltification, but water temperature can affect and halt this process including outmigration (Wagner 1974, Zaugg 1981). Bjornn & Reiser (1991) observed that the parr-smolts transformation is often incomplete when the fish begin to migrate and may fail to develop fully if the fish encounters high temperatures and reservoirs without perceptible currents.

The results of our literature review and the reviews of others indicate that the salmonid smolting process is adversely affected when temperatures reach a threshold level of 12 - 13 °C, and that outmigration may be stopped when water temperatures increase to 15 - 17 °C.

In an overall review of the salmonid smolting requirements, McCullough et al. (2001) conclude that these fish experienced reduced ATPase levels at temperatures greater than 11 - 13 °C. They also note that temperatures of 14 - 15 °C may stop outmigration. Another review by Wedemeyer et al. (1980) found that 12 - 13 °C is a threshold beyond which the smolting process for chinook and coho salmon and steelhead trout is disrupted or halted. A review by Myrick & Cech (2001) that focused on central California chinook salmon and steelhead populations found that temperatures greater than 15 - 16 °C impaired smoltification and salt water survival.

The following laboratory research further defines temperature levels affecting smoltification and outmigration. Clarke & Shelbourn (1985) found that freshwater rearing temperature and time of transfer are the most important factors influencing the ability of juvenile fall chinook salmon to regulate plasma sodium concentrations and grow in sea water. Osmoregulatory preadaptation to sea water was best when fish reared in 10 - 17.5 °C freshwater were transferred to sea water from early May onwards. Clarke & Shelbourn (1980) observed the greatest hypoosmoregulatory capacity in coho salmon at 11 - 15 °C. Brett et al. (1958) found that 12 - 14 °C stopped the downstream migration of juvenile sockeye salmon. Zaugg & Wagner (1973) found that steelhead trout had decreased ATPase and reduced migration at temperatures at and above 13 °C.

An 8-year field study by Foerster (1937) on juvenile sockeye salmon in Cultus Lake, BC revealed that as the surface temperature of the lake approached 13 °C outmigration of native fish decreased greatly. Thereafter only stragglers appeared in the migration, which stopped completely when the temperature reached 14 - 20 °C (averaged 17.5 °C).

Adult salmonid migrations back to their natal streams are also affected by water temperature. Water temperatures that enable upstream migration to occur are 10.6 - 19.4 °C for fall chinook, 3.3 - 13.3 °C for spring chinook, 13.9 - 20 °C for summer chinook, and 7.2 - 15.6 °C for sockeye (Bell 1986). Delays in upstream migration because natal streams are too warm have been observed for all of the salmonid species being considered in this assessment. These migrations appear to be impaired or blocked when water temperatures exceed 21 °C (Fish & Hanavan 1948, Major & Mighell 1966, Hallock et al. 1970, Monan et al. 1975, Stabler 1981, and Farrell 1997).

A comprehensive review by McCullough et al. (2001), found that migration blockages occur consistently among salmonid species in the temperature range 19 - 23 °C. The adults cope with the increased water temperatures during migration by using thermal refugia (Fish & Hanavan 1948, Berman & Quinn 1991, Nielsen et al. 1994), but this delay in their upstream migration may subsequently affect their reproductive capacity.

4.2.4 Effects of increased water temperature on the virulence of fish diseases

Water temperatures in many rivers in the Pacific Northwest from May through October are in a range favorable for the development of important salmonid infectious diseases (Fryer et al. 1976). These diseases, which are the result of bacterial, viral, or parasitic infections, can adversely affect juvenile and adult fish populations. Within the study area, sympatric fish species that are resistant or have survived past infections are the likely source of infection. When environmental conditions including water temperature become optimal, the disease may infect a susceptible host, grow and may become virulent. In a review of the effects of freshwater pathogens on wild and captive salmonid populations, Hicks (2001) arrived at the following conclusions: average temperatures below 12 - 13 °C significantly and often completely eliminate both infection and mortality, average temperatures above 15 - 16 °C are often associated with serious rates of infection and mortality, and average temperatures above 18 - 20 °C are commonly associated with very serious infections and often catastrophic outbreaks of many diseases.

With some exceptions, the results of numerous laboratory and field studies generally support Hicks' findings. Laboratory-induced infections of juvenile coho and spring chinook salmon and juvenile steelhead with ceratomyxosis (*Ceratomyxa shasta*) and columnaris (*Flexibacter columnaris*) follow this pattern (Fryer & Pilcher 1974, Udey et al. 1975, Fryer et al. 1976, Groberg et al. 1978). This same pattern is supported by a field study from the Fraser River, where Ching & Munday (1984) observed 95% mortality due to ceratomyxosis in 6 stocks of juvenile chinook salmon naturally infected during a 10-day exposure period at a mean temperature of 16.9 °C. An exception may be found in a study that exposed spring chinook, coho, and sockeye salmon to *C. shasta* while being held captive in the Willamette River (Zinn et al. 1977). These three species incurred low to moderate mortality during an exposure at temperatures ranging from 14.5 - 17 °C.

For adults, high mortality in laboratory-held spring chinook salmon at 17.5 - 19 °C and sockeye salmon at 20 °C was observed due to columnaris infections (Berman 1990, Bouck et al. 1975). Also, Colgrove & Wood (1966) observed that columnaris disease seldom occurred in adult sockeye salmon at temperatures below 12.8 °C, and that temperatures above 15.6 °C appeared necessary to initiate the pathological effects of the disease. Finally, Mackie et al. (1933) report that water temperatures must be greater than 12.7 °C for a serious furunculosis epizootic to occur in nature.

Any recommendation for temperatures to control fish disease should consider the effect of other stressors affecting the virulence of the disease. For example, Maule et al. (1989) noted that juvenile chinook salmon had lower resistence to infection and decreased ability to mount an immune response following an acute stress exposure. Also, different strains of a given disease may be more or less virulent (e.g., columnaris in juvenile sockeye salmon, Pacha & Ordal 1970), virulence may not be closely related to water temperature (e.g., bacterial kidney disease in juvenile coho salmon or steelhead, Fryer et al. 1976), or virulence may be highest at low temperatures (e.g., *Cytophaga psychrophila* in juvenile coho salmon, Ordal & Pacha 1963).

4.2.5 Effects of increased temperature on predation

Increased predation associated with rising water temperatures in the Columbia River basin is mainly an issue with downstream migrating juvenile salmonids. Water temperature has both direct and indirect effects on predation. Direct effects are realized when fish are weakened or shocked by high temperatures and become more susceptible to predation. Indirect effects occur when migratory pathways used by juvenile salmonids become more suitable for warm-water predators, when shallow water rearing areas become too warm for juvenile fish and they move into deeper water inhabited by predators, or when fish are weakened by diseases made more virulent by increased temperatures and become easier prey than healthy fish.

Limited information is available on shock effects caused by high water temperatures, and most of this research was done to assess salmonid survival in thermal discharges. At high water temperatures fish can lose their equilibrium in the water column and become easy prey. Coutant (1973) found that juvenile chinook salmon exposed to 28 °C for 1.1 to 5.6 minutes (10 to 50 % of the duration needed to cause complete loss of equilibrium) resulted in increased predation after the fish were returned to 15 °C. It may be difficult, however, to relate these exposures to environmental conditions in the reservoir system of the Columbia and Snake rivers where such steep (i.e., 13 °C) changes in temperature probably do not occur. Nonetheless, this study is demonstrative of an effect that may occur at lower temperature differentials.

As the water in the main channels and reservoirs of the Columbia and Snake rivers increases above 16 °C each summer, habitat conditions for predatory fish species improve. The northern pikeminnow (*Ptychocheilus oregonensis)*, walleye (*Stizostedion vitreum*), smallmouth bass (*Micropterus dolomieu*), and channel catfish (*Ictalurus punctatus*) are important fish predators inhabiting the reservoirs; but the pikeminnow is clearly the major predator on juvenile salmonids (Vigg et al. 1991, Mesa 1994). The preferred temperature ranges for the northern pikeminnow, walleye, smallmouth bass and the channel catfish are 16 - 22 °C, 21 - 23 °C, 20 - 21.7 °C and >21 °C, respectively (Vigg et al. 1991, Bell 1986). The prey consumption rates for these predators were highest in John Day Reservoir in July concurrent with maximum water temperature and the highest abundance of juvenile salmonids (Vigg et al. 1991). In tests conducted by Vigg & Burley (1991), peak consumption of juvenile salmonids by northern pikeminnow was near 21.5 °C, but these authors recommended further work to better define optimum temperatures for consumption and growth.

Increased water temperatures in shallow habitats is also an area of concern. Some juvenile salmonids feed in shallow water areas that have protective cover from predators on the margins of the Columbia and Snake rivers, including the reservoirs. As the water temperature increases in these areas they become less hospitable for juvenile fish, which then move into cooler, deeper water lacking cover and where predators are more common. Curet (1993) and Connor et al. (1999) noted subyearling chinook salmon moved from shoreline to pelagic areas in the Snake River when water temperatures increased to 17 - 19 °C; however, they did not document that this caused increased predation.

Predation of fish weakened by disease made more virulent by increasing water temperatures is likely secondary to the concern for the actual loss of fish due to the disease. Once fish are infected by a disease, recovery may not occur unless the water temperature drops. Nonetheless, sublethal infections may cause fish to be more prone to predation than healthy fish. Mesa et al. (1998) observed that juvenile chinook salmon infected with bacterial kidney disease (*Renibacterium salmoninarum*) were eaten by either northern pikeminnow or smallmouth bass in significantly greater numbers than control fish by nearly two to one.

Fish affected by multiple stressors in combination with high water temperature are also likely to be more susceptible to predation. In laboratory studies, Mesa (1994) found that juvenile chinook salmon subjected to multiple handlings and agitations became lethargic and more prone to predation by northern pikeminnow. Multiple stresses are more likely to occur when juvenile salmonids pass through dams during their outmigration. Increased water temperatures are commonly observed in the forebay areas of dams and the fish are then subjected to the stresses of being routed through the fish bypass structures or withstanding the pressure differentials as they negotiate passage through the turbines.

4.2.6 Effects of increased temperature on fish distribution

The distribution of native salmonids in aquatic habitats is strongly tied to natural thermal regimes, which in the Columbia River basin have been significantly modified by past anthropogenic influences such as dam construction and operation and water withdrawals. Natural shifts in the regimes like droughts have only added to the adverse effects of increased water temperature. When water temperatures exceed the preferred or optimal ranges for salmonids, their distribution is usually restricted. Laboratory studies have demonstrated that temperature alone can control the distribution of fish (Ferguson 1958), and that fish density within their habitats can be reduced at higher temperatures (Hahn 1977).

Juvenile coho salmon prefer a temperature range of 12 - 14 °C, which is close to optimum for maximum growth efficiency (Brett 1952). Several field studies have demonstrated the reduction in coho distribution when water temperature exceeds this optimum range. Two studies in the Sixes River basin in southwest Oregon found that juvenile coho were rare or absent in stream reaches that exceeded 20 - 21 °C (Stein et al. 1972, Frissell 1992). In a study of 21 tributaries of the Mattole River in northern California, Welsh et al. (2001) noted that juvenile coho salmon were always present when the average and maximum daily temperatures over a 7-day period (maximums for the entire summer) were <14.5 °C and <16.3 °C, respectively. At higher temperatures, the same study found that coho are usually restricted from tributaries when these average and maximum temperatures are >16.8 °C and >18.1 °C, respectively. In a study of three streams affected by the Mt. St. Helens eruption, Bisson et al. (1988) found that planted juvenile coho lived in streams where the average daily minimum temperatures ranged from 11 - 15 °C and maximum temperatures ranged from about 15 - 24 °C during July and August. Survival or retention of the planted fish ranged from 5.9 to 48.8% in these streams, but those that stayed grew at rates comparable with those in similar sized streams in the region. The results of these studies tend to support Brett's (1952) preferred temperature range, but they also show that in some cases coho can withstand higher temperatures but at reduced population numbers. At higher temperatures other factors such as unlimited food and lack of competition may enable these fish to survive.

The upper limit of the preferred range for juvenile chinook salmon is also about 14 °C (Brett 1952, Bell 1986). However, in sympatric relationships with coho, juvenile chinook salmon appear to be able to withstand higher temperatures. As the temperature of the Sixes River (Oregon) increased above 20 °C, chinook continued to reside after coho had departed (Stein et al. 1972), but 23 °C may be the maximum temperature for limiting their distribution in this river (Frissell 1992). Other studies, however, indicate the distribution of juvenile chinook salmon is affected at much lower temperatures. As previously mentioned, shallow water feeding areas in the Snake and Columbia rivers appear to become unacceptable to subyearling chinook salmon when the temperature in these areas exceeds 17 - 18 °C (Becker 1973, Curet 1993, Connor et al. 1999).

The upper limit of the optimal range for juvenile steelhead trout is 12.8 °C (Bell 1986). This species, however, may be able to successfully live at higher water temperatures in the southern part of its range. Cech & Myrick (1999) found that juvenile Nimbus strain steelhead, a fish native to California, has a higher thermal preference over a 11 - 19 °C range. At water temperatures of 19 - 22 °C, the distribution of steelhead in more northern parts of its range can be reduced by competition from non-salmonid sympatric fish species (Reeves et al. 1987).

4.2.7 Other sub-lethal and lethal effects of increased water temperature

Sub-lethal effects, not previously discussed, include impaired reproduction, neuro-endocrine and endocrine reactions, disturbances in osmotic and ionic regulation, and modified behavior. Lethal effects from increased water temperature can be acute, causing death in hours, or chronic, which causes death to occur over a longer period of time. Comprehensive reviews of sub-lethal and lethal effects of high temperature exposures on salmonids have been completed by Brungs & Jones (1977), Bell (1986), Marine (1992), Berman (1998), Cech & Myrick (1999), McCullough (1999), Sullivan et al. (2000), Myrick & Cech (2001), McCullough et al. (2001) and Hicks (2001). The following discussions are a summary of the findings of some of these reviews and of some individual studies.

4.2.7.1 Effects on reproductive capacity

If gravid adult salmonids are exposed to high water temperatures prior to spawning, their reproductive success can be affected. High water temperatures affect the vitality of their gametes (McCullough et al. 2001). Several studies have demonstrated this adverse effect.

In a review of the effects of elevated water temperature on the reproductive performance of adult chinook salmon, Marine (1992) reported that 15 - 17 °C led to sub-lethal effects in brood stock and caused increased infertility and embryonic developmental abnormalities. Berman (1990) observed that reproductively mature spring chinook salmon from the Yakima River held at 17.5 - 19 °C produced a greater number of pre-hatch mortalities and developmental abnormalities, as well as smaller eggs and alevins than adults held at 14 - 15.5 °C. In the American River in California, Hinze et al. (1956), noted that egg eye-up rates exceeding 55% did not occur when eggs were taken from fall chinook salmon exposed to river water exceeding 15.5 °C. Similarly, Bouck et al. (1975) observed reduced reproductive capacity in adult sockeye salmon held at 16.5 °C as compared to 10 °C.

In adult coho returns from Lake Erie, Flett et al. (1996) partially attributed a decline in the quality of ovulated eggs to exposure of adults to surface water temperatures exceeding 20 °C.

4.2.7.2 Physiological and behavioral effects

Fish respond physiologically (altered growth and health) and behaviorally (movement, site selection, and interactions) to environmental conditions they encounter. Chronic stress caused by elevated temperatures directly affects these physiological and behavioral parameters and weakens the resistance of salmonids to other stressors (Thomas et al. 1986). Other than growth, the biological significance of the physiological changes caused by exposures to high water temperatures are not fully understood. Measurements of plasma cortisol and glucose or liver glycogens are commonly measured stress indicators in fish. If these measurements are to have application beyond research, they must be relatively uniform over a wide range of conditions. For example, the possible differences caused by additional stress and non-stress factors such as age, size, and nutritional status of the fish must be considered (Barton & Schreck 1987).

For this assessment, we used an alternative approach for identifying water temperatures causing adverse physiological and behavioral conditions. By definition, the most favorable physiological conditions for fish occur within the optimum temperature range for that species. The upper limit of the optimum range is 14 °C for chinook salmon (Brett 1952), 15 °C for sockeye salmon (Brett 1967), 14 °C for coho salmon (Brett 1952), and 14 - 15 °C for steelhead trout (Hicks 2001). Water temperatures exceeding the upper limits of these optimum ranges can be expected to cause physiological and behavioral responses as the fish adjust to their warmer environment. On a small scale, these adjustments may be measured by increased levels of glucose or cortisol in blood plasma or the depression of liver glycogens. On a larger scale, particularly in combination with other stresses, the health and survivability of the fish can be affected. For example, Barton & Schreck (1987) observed 40% mortality in juvenile fall chinook salmon exposed to crowding stress and 21 °C and no mortality in fish held at 7.5 °C with the same crowding stress.

4.2.7.3 Lethal effects

The lethal effects of high water temperatures for each salmonid species are summarized in Tables 4.1 to 4.5. They are not reviewed in detail here as these temperatures are well beyond what would be considered adequate for protecting the important fish species in the Columbia River basin.

4.2.8 Effects of increased temperature on adult bull trout

Bull trout occur across a major portion of their potential range in the Columbia River basin and are more commonly found in cold, high-elevation, low to mid order watersheds with low road densities (Ratliff & Howell 1992, Rieman et al. 1997). Due to habitat degradation and fragmentation, blockage of migratory corridors, poor water quality, past fisheries management practices, and the introduction of non-native species, the bull trout was listed in 1998 as threatened under the ESA (Lohr et al. 2001). Laboratory survival experiments by Selong et al. (2001) corroborate field observations suggesting that bull trout have among the lowest upper thermal limits of the North American salmonids.

Adult bull trout are known to move downstream in watersheds to overwinter in mainstem or reservoir areas (McPhail & Murray 1979, Fraley & Shepard 1989, Schill et al. 1994). Distances traveled between the tributaries and downstream overwintering areas commonly exceed 100 km (Schill et al. 1994, Swanberg 1996), and movements up to 275 km have been recorded (Burrows et al. 2001). Adult bull trout are believed to occasionally use nearly all mainstem and reservoir areas in the study area (Mongillo 1993). Life cycle requirements of concern for adult bull trout found in these areas are the effects of increased water temperature on growth, movement and distribution.

Field and laboratory growth studies for adult bull trout in relation to water temperature are not available. In a laboratory study with age-0 bull trout fed to excess, Selong et al. (2001) estimated by regression analysis that peak growth occurred at 13.2 °C. Above this level, the growth rate decreased sharply, falling to 60% and 19% of the peak growth rate at 18 °C and 20 °C, respectively (ibid.). Without qualification, it would be inappropriate to directly relate this laboratory growth study on juveniles to field conditions for adults. Nonetheless, it is indicative of the low temperature requirements needed for the growth of this species.

As with other salmonids, water temperature affects bull trout movements. Adult bull trout migrations usually occur at 10 - 12 °C (Buchanan & Gregory 1997) and water temperatures of 16 - 18 °C are believed to cause thermal blocks (Shepard 1985, M. Faler, personal communication cited in Thiesfeld et al. 1996). Their movements into tributaries appear to occur with both increasing and decreasing temperature cycles. With increasing water temperatures, adult bull trout moved from Upper Arrow Lake reservoir into MacKenzie Creek in British Columbia (McPhail & Murray 1979); from the Salmon River into Rapid River in Idaho (Elle 1995); and from the Blackfoot River into its tributaries in Montana (Swanberg 1996). Conversely, adults moved with decreasing water temperatures from the Flathead Lake to the North and Middle Forks of the Flathead River in northern Montana and southern British Columbia (Fraley & Shepard 1989); and from Lake Cushman to the North Fork of the Skokomish River on the Olympic Peninsula (Brenkman et al. 2001). Except for the study on the Blackfoot River, the threshold temperature for when fish moved was 10 - 12 °C. Fish began to move in the Blackfoot River at temperatures ranging from 12 - 20 °C (mean 17.7 °C). All of the above movements were spawning migrations and all, except for the one on the Olympic Peninsula, were in the Columbia River basin, and the movements occurred from approximately March through November.

The upper limit of the optimum range for the bull trout appears to be at or near 12 °C. Oregon Department of Environmental Quality (1995) identified a preference range of 9 - 13 °C for adult bull trout. Shepard et al. (1984) and Haas (2001) respectively found bull trout in the greatest densities and in the best condition at temperatures ≤12 °C. When water temperatures increase to levels exceeding their optimum range for bull trout, their distribution is reduced. Under these conditions, bull trout will move from the free-flowing main channel reaches or reservoirs within the study area to their natal streams or into thermal refugia.

4.3 Non-Salmonids

In the Columbia River basin, white sturgeon are present throughout the area of concern for this problem assessment. Their population numbers are stable in Lower Columbia River and in some of the reservoirs with contiguous upstream free-flowing reaches. However, in other reservoirs lacking critical spawning or rearing habitat their population numbers may be depressed (Coon 1978, Lepla 1994, North et al. 1993, Parsley et al. 1993, Devore et al. 1995, Beamesderfer et al. 1995).

Other cold-water fish species inhabit the area of concern for the problem assessment but their critical life stages are either not well defined, or they occur mainly in the tributaries to the main channel areas that are the subject of this problem assessment.

4.3.1 Effect of increased temperature on white sturgeon reproduction

White sturgeon spawn in main channel areas with high current velocity from April through July (Parley et al. 1993, McCabe & Tracy 1994). A high discharge rate (flow) appears to stimulate spawning activity. Water temperature is not an acute spawning cue as are high river discharge and water column velocity (Andres & Beckman 1995).

The amount of spawning habitat for white sturgeon is defined by the discharge rate and water temperature in the river. As the rate increases, areas with high water velocity increase, and the spawning period is further defined by the temperature range within which successful spawning occurs (Parsley & Beckman 1994). This fish spawns in water temperatures ranging from 10 - 18 °C, with most spawning occurring at 14 °C (Parsley et al. 1993). Successful egg incubation is possible with a temperature range of 10 - 18 °C, but best results occur at 14 - 16 °C. Temperatures 18 - 20 °C may cause substantial mortalities during sensitive embryonic stages, and temperatures above 20 °C are clearly lethal of white sturgeon embryos. Fungal infection of the developing eggs is also a concern with increased water temperatures. The embryonic stage of the white sturgeon is about 3 weeks long at 17 °C (Wang et al. 1985).

Upon completion of their embryonic stage, white sturgeon appear to be able to successfully withstand water temperatures higher than 18 - 20 °C. Cech et al. (1984) noted that growth of post-embryonic white sturgeon increased significantly from 15 - 20 °C, but there was no significant different from 20 to 25 °C.

4.4 Summary of the effects of increased water temperature on native fish

Two levels of concern for the effects of increased water temperature on chinook, sockeye, and coho salmon, steelhead and bull trout, and white sturgeon are provided in Table 4.6. They are levels of “Initial” and “Serious” concern. The level of initial concern is lowest level that may cause the adverse effect and, where needed, the agent causing the effect is also present (e.g., disease or a predator). The level of serious concern is when a fish population is exposed to conditions that will very likely cause the adverse effects listed in Table 4.6.

The temperature levels listed are intended to be for the above listed fish species as they occur in the Columbia River basin. In some cases fish, e.g., chinook salmon and steelhead trout, occurring in the southern part of their range in North America can withstand water temperatures higher than those discussed in the effects sections (Cech & Myrick 1999, Myrick & Cech 2001). Further, where information is not available or the information available does not allow for the listing of a temperature, a dash (i.e., “-“) is provided. Also, note that the temperature requirements for bull trout are listed separately from those of the other salmonids.

From an overall review of the levels of initial concern, with some exceptions, it appears that most of the adverse effects will begin to occur as water temperatures increase to 13 - 15 °C. The exceptions at lower temperatures are the requirements for steelhead smoltification (<12 °C) and for low temperature levels (<12 °C) required by adult bull trout. The exceptions at higher temperatures (16 - 18 °C) are reduced salmonid growth, reduced chinook distribution, increased predation, and impaired bull trout holding and migration.

In a similar review of the levels of serious concern, there is some overlap because of the low temperatures required for smoltification of chinook, sockeye, and steelhead. The remainder of the temperatures fall in the 18 - 22 °C range. It should also be noted that as water temperatures increase into the 20+ °C range chronic and acute toxicity become a concern, particularly if the fish are sustaining multiple stressors, like passing through dams.

Except for bull trout, the time periods of concern for resident and migratory salmonids are shown in Figure 4-1. The time period of concern for bull trout would vary with location in the Columbia and Snake rivers within the study area, but would generally be during the late summer and early fall when adult fish are moving out of main channel areas into tributaries.

The time period of concern for fall chinook salmon spawning is from mid-October to the third week of November in the Columbia River and from mid-October to mid-December in the Snake River (Dauble & Watson 1997, Tiffan et al. 1999, Groves & Chandler 1999). Growth is an issue all year for yearling salmonids, and for subyearlings it is an issue from early March to mid-late September. The time periods of concern for outmigrating juvenile salmonids extend from early April to mid-late September, depending of the species. Returning adult salmonids are likely in the river all year long, but begin arriving in numbers at Bonneville Dam in early March and continue up the Columbia River until about mid-November and up the Snake River until early-mid December.

The period of concern for white sturgeon spawning and incubation is from April through August each year. Depending on the location in the river, white sturgeon may spawn from the end of April through July (Parsley et al. 1993, McCabe & Tracy 1994). The spawning period is followed by a 3-week incubation period (Wang et al. 1985).

Excluding fish species usually found in the estuary, there are about 20 families of fish that occur in the study area, of which 10 are native (Wydoski & Whitney 1979). This assessment covers the temperature requirements for two of these families, which includes all fish species listed under the Endangered Species Act and nearly all fish of commercial and recreational importance.

Table 4.6 Summary of the effects of increased water temperature on the important fish species of the Columbia River basin.

Effect/Concern - Salmonids	**Water Temperature (°C)**	
	Initial Concern	**Serious Concern**
Increased mortality to eggs incubating in the gravel[1]	14	-
Abnormal egg/larval development resulting from the exposure of adults to high temperatures[1]	15	17
Impaired juvenile pre-smolt physiology, excluding growth		
- Chinook salmon	>14	-
- Sockeye salmon	>15	-
- Coho salmon	>14	-
- Steelhead trout	>14	-
Impaired adult bull trout physiology	>12	-
Impaired smoltification, slows or halts outmigration		
- Chinook salmon	13	15
- Sockeye salmon	13	15
- Coho salmon	14	17
- Steelhead trout	12	14
- Bull trout	-	-
Reduced growth by juveniles[1]	18	21
Reduced growth by subadult and adult bull trout	16	18
Reduced juvenile distribution		
- Chinook salmon	17 - 18	20 - 22
- Sockeye salmon	-	-
- Coho salmon	15	18
- Steelhead trout	-	20 - 22
Reduced distribution of subadult and adult bull trout	13 - 14	16 - 18
Increased predation on juveniles[1]	16	21
Increased disease	15 - 16	18 - 20
Adult migration stopped[1]	-	21
Adult bull trout migration and holding impaired	16	-
Effect/Concern - Non-Salmonids	**Initial Concern**	**Serious Concern**
White sturgeon fail to reproduce or have an unsuccessful 3 - week incubation	>17	>18

Notes: 1. Does not include bull trout.

Figure 4-1. Time periods of concern for subyearling, yearling, and adult salmonids moving through or residing in the study area.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	References
Spawning **Fall Chinook**													